Western wonders under the microscope: building a micromorphology reference collection for northwest Australia

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Abstract

Micromorphology is an effective and useful tool for documenting and differentiating cultural and non-cultural (including post-depositional) contextual features within archaeological matrices. Archaeological micromorphology is still a nascent field in Australia and, more generally, in arid and semi-arid environments, and as such would benefit from a reference collection to help identify cultural and non-cultural remains and features in this region. Here we introduce the beginnings of an archaeological micromorphological reference collection themed around material from northwest Australia. Reference material includes lithogenic and biogenic components such as stone artefacts, shells, plants and scats from native fauna and sedimentary contextual features from archaeological sites in the Kimberley and coastal Pilbara regions. This reference collection is useful for teaching and research, including regional Quaternary studies, and we encourage the development of similar regional micromorphological datasets for other parts of the continent and dryland environments more generally.

Keywords: Micromorphology, reference, archaeology, northwest Australia

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INTRODUCTION

Micromorphology is the microscopic study of oriented, undisturbed (relative to bulk samples) sediment samples to describe, measure and interpret the spatial relationship of the constituent materials. It is increasingly used in geoarchaeological studies to aid palaeoenvironmental reconstruction and help unravel lithogenic and anthropogenic inputs and formation processes in archaeological sites (Goldberg & Aldeias 2018). A key aspect of this is understanding the contribution of people not just with lithics, bones or plants but also on the original sedimentary signal (Stein 1985) and role of sediments themselves as 'artefacts' (Goldberg & Berna 2010). Both soil micromorphology and archaeological micromorphology are well used and developed in cold or temperate contexts in Northern Hemisphere (Sageidet 2000; van der Meer & Menzies 2011; Nicosia & Stoops 2017).

Despite the foundational work of Brewer (1964) on soil micromorphology in Australia, micromorphology remains a nascent but growing field here. Emerging post-graduate studies highlight the potential of this technique for understanding and interpreting the archaeological sediments and the objects they enclose (e.g. Venn 2008; Murszewski 2013; Murszewski *et al.* 2014; Jankowski 2014, Jankowski *et al.* 2015; Lin 2016; Lowe *et al.* 2016; Vannieuwenhuyse 2016; Vannieuwenhuyse *et al.* 2017). In semi-arid environments, soil micromorphological studies are helpful to determine palaeoenvironments, palaeoclimate (e.g. Courty & Fédoroff 1985; Singhvi & Derbyshire 1999) and past cultivation [1] (Presley *et al.* 2014; Verba *et al.* 1995). Less foundational work has been done on archaeological micromorphology in humid tropical regions (though see Friesem *et al.* 2016; Morley & Goldberg 2017 and references therein) and arguably even less in hot dryland contexts where processes are greatly influenced by eolian deposition where natural and cultural contributions are primarily inorganic in nature.

One way to help advance and teach this technique is to create a micromorphological reference collection of archaeological (including stone artefacts, shell, bone, charcoal remains), and associated environmental material that may be found in different sites and contexts around Australia. Also useful are reference slides of microstructures and features that relate to a particular sedimentary context, building on what is already known from soil micromorphology (e.g. Courty & Fedoroff 1985; Stoops *et al.* 1993; Amit & Yaalon 1996). In effect this constitutes a drylands-focused response to Courty's (1991) call to progress archaeological micromorphology by building and publishing reference systems that are accessible to all archaeologists.

[1] Of interest is a recent application of soil micromorphology to look at historic evidence of water and soil management in a semi-arid part of Tanzania. See https://www.ramsar.org/archaeological-evidence-for-shifting-irrigation-and-cultivation-practices-at-engaruka-tanzania

Building a northwest Australian micromorphological reference collection

Northwest Australia covers a large diversity of landscapes and climatic zones from arid coastlines of the Pilbara, through inland deserts to the semi-arid tropics of the Kimberley. These environments also comprise a wide array of rocks ranging from the Archaean sedimentary and volcanic formations of the Pilbara to the Phanerozoic sedimentary rocks of the Kimberley (Figure 1). These broad rock units not only provide sites for caves and rockshelters but also the material from which stone artefacts are manufactured.

This paper presents an overview of lithogenic (stone artefacts) and biogenic reference material (shells, scats, botanical samples) from the Pilbara and the Kimberley. As no micromorphological reference collection currently exists for Australia, the applied aspect of such a reference collection is largely synthetic and here based on previous and current micromorphological studies in the Devonian Ranges of the Kimberley – Carpenters Gap 1, Riwi and Mount Behn (Vannieuwenhuyse 2016), Boodie Cave (Ward *et al*. 2017), and Dampier Archipelago in the Pilbara (Figure 2). The objectives of archaeological micromorphology are contextual: to consider human activities through time and through space by analysing spatio-temporal relationships between the sedimentary matrix and its artefactual content (Courty 1991). Hence, we also incorporate 'contextual' slides relating to midden deposits, hearth/ash features, wall spall containing pigment, post-depositional structures, and sediments containing stone artefacts and plant fragments from the study areas into the reference collection. This preliminary work is intended to highlight the value in further developing micromorphological reference collections for the northwest and also in other parts of Australia.

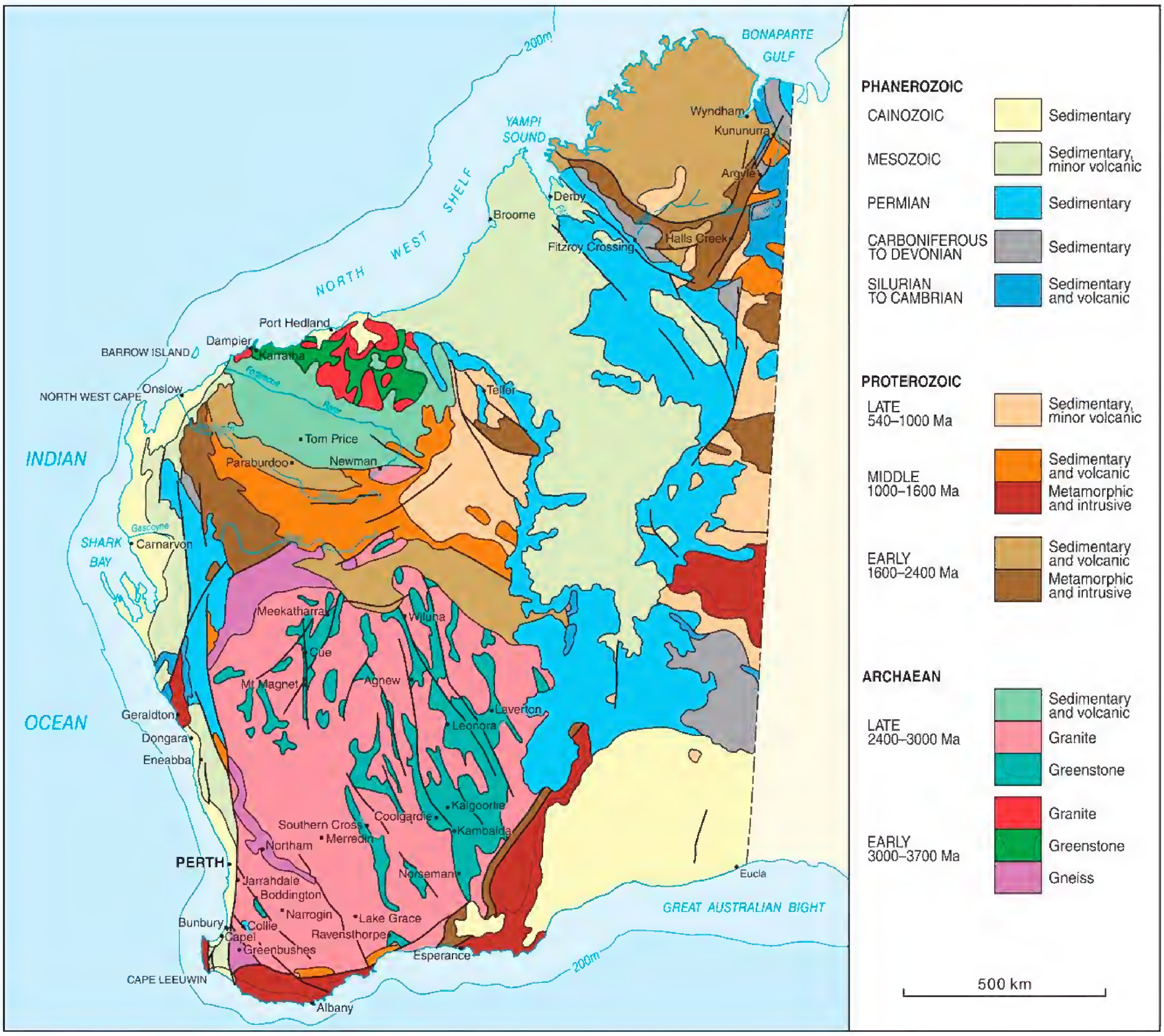

Figure 1. Simplified geology of Western Australia (from Martin *et al*. 2015).

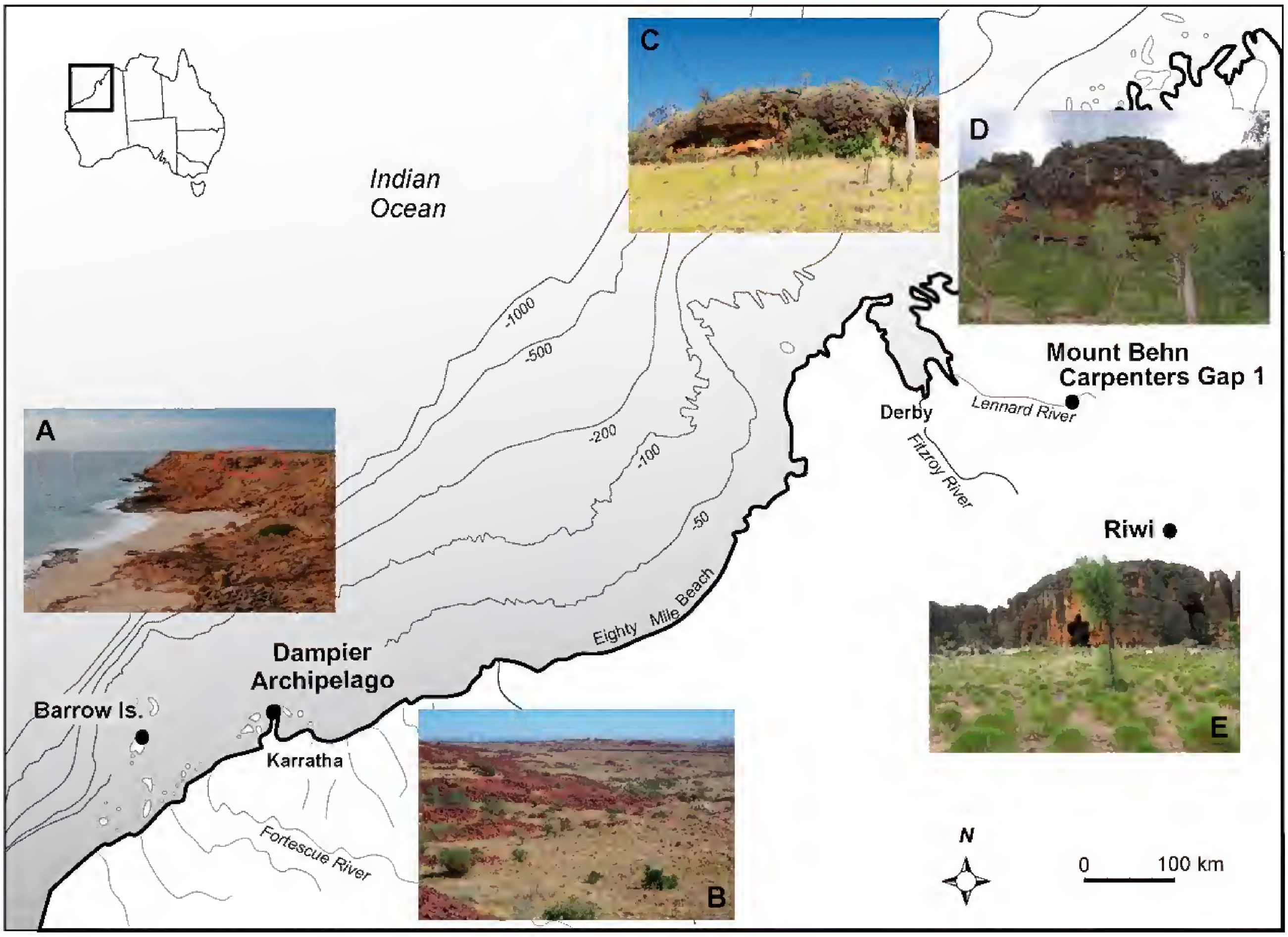

Figure 2. Map of northwest Australia showing sites mentioned in text including: A, Boodie Cave; B, Burrup Peninsula (Dampier Archipelago); C, Mount Behn; D, Carpenters Gap 1; E, Riwi.

METHODS

Lithologic (stone artefacts, spalled rock) and biogenic reference material (shells, scats, botanical samples) were obtained from field collection or archaeological surveys and excavations. Mollusc shell samples were largely obtained from samples collected by University of Western Australia (UWA) archaeology staff, and supplemented where necessary with modern samples. Species include the baler shell (*Melo* sp.), *Nerita lineata*, mangrove whelk (*Terebralia palustris*) and landsnail (*Rhagada ballarensis*) among the Gastropoda; oysters (Ostredidea) and pearl shells (Pinctada) among the Bivalvia; and limpet shells (Patelloida). In addition, there is also eggshell from marine turtles (Chelonioidea) and birds (Cacatuidae).

Scats from native fauna that occupy caves and rockshelters on Barrow Island were especially collected by the Western Australian Department of Parks and Wildlife for this study. Barrow Island is a Class A reserve hence collections from this island ensure that any decomposed material within the scats represents native rather than introduced vegetation. Seven species are represented including the herbivorous euro (*Macropus robustus isabellinus*), black-flanked rock wallaby (*Petrogale lateralis lateralis*), northern brushtail possum (*Trichosurus vulpecula arnhemensis*), and the omnivorous golden bandicoot (*Isoodon auratus barrowensis*), burrowing boodie (*Bettongia leseur*), the insectivorous Finlayson's Cave bat (*Vespadelus finlaysoni*) and the carnivorous perentie (*Varanus giganteus*).

Stone artefact, shell and scat samples were prepared for thin sectioning by resin impregnation (using a 7:3 mix of polyester resin with styrene) of discrete samples in ice-cube trays, which were then made into 2.5 x 5 cm polished thin sections. Stone artefact samples were obtained from field collections and include (siliceous-) sedimentary, igneous, metamorphic and meta-sedimentary rocks. Where possible comparisons are made with 'contextual' thin sections from previous micromorphological studies undertaken in the Kimberley (Vannieuwenhuyse 2016) and Pilbara (Ward *et al.* 2017). These larger (5 x 7 cm) contextual thin sections were made by Spectrum Petrographics in the USA from resin-impregnated coherent sediment blocks taken from archaeological excavation profiles, and are more suitable to document depositional and post-depositional features.

Slides were scrutinised using a polarising petrographic microscope available at UWA under plane polarised light (PPL) and crossed-polarised light (XPL) using different magnifications (10x, 25x, 50x, 100x, 500x). The terminology used follows Stoops (2003), Stoops *et al.* (2010), and Nicosia & Stoops (2017).

RESULTS

Lithogenic Fraction

STONE ARTEFACTS

One of the primary criteria for distinguishing stone artefacts in micromorphological sections is their raw material. Past people often selected materials for stone artefact manufacture based on specific attributes such as their size, shape and quality (e.g. Braun et al. 2009; Harmand 2009; Ditchfield 2016). This can make stone artefacts easy to distinguish in micromorphological sections when the raw materials are different to the sediments in which they were discarded (Figure 3) but much less so when they are manufactured from a similar (local) lithology (e.g. Ward *et al.* 2017). Most stone artefact assemblages in Western Australian archaeological sites are characterised by an extraordinary range of lithologies, particularly in the geologically diverse Pilbara region (Hickman 1983). These include a wide range of igneous (e.g. granite, basalt, dolerite), sedimentary (e.g. chert, limestone, silcrete, banded iron formation), metasedimentary (e.g. slate) and metamorphic (e.g. mylonite) rock types (Figure 1). Hence, we know very little about geological source locations beyond broad inferences of 'non-local' versus 'local' availability. This is further complicated by limited petrographic data, incomplete detailed geological mapping (with many geological units exceeding several hundred kilometres), unknown potential quarry locations and also limited stratigraphic information with which to assess changes in lithology and their sources (Martin 1982). This situation is improving with updated geological maps (e.g. Martin *et al.* 2015) and localized studies (by government agencies, university researchers, and industry) within these broader regions.

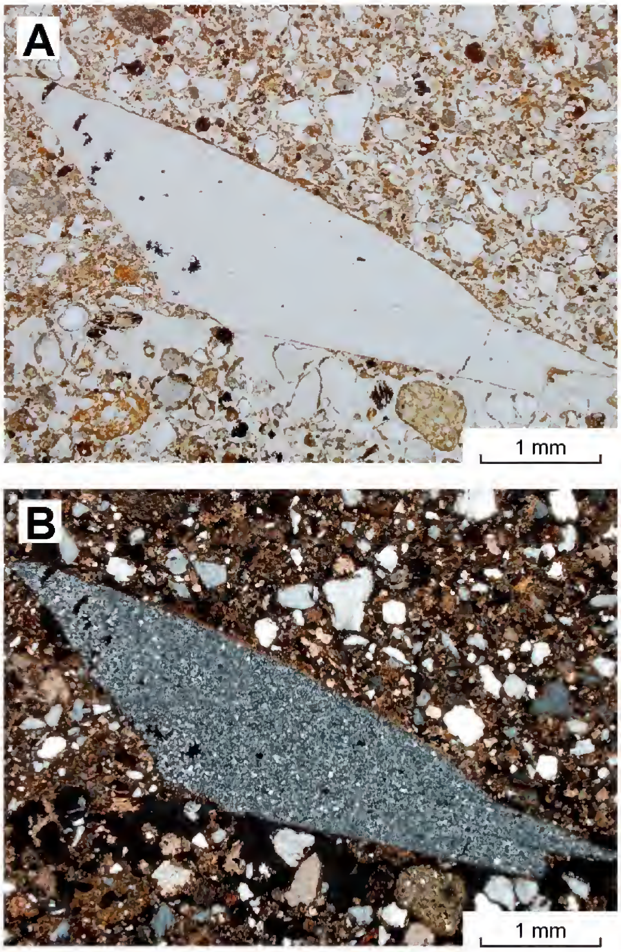

Figure 3. Example of lithic artefact from Mount Behn sequence, Kimberley (sourced from Vannieuwenhuyse 2016). Note the sharp edges and the cryptocrystalline siliceous nature (probably chert) of the artefact, which contrasts with the quartz dominated surrounding sandy matrix (A, PPL; B, XPL).

Where stone artefacts are manufactured from material similar to that in their geological and/or sedimentary environment, other attributes can be used. Stone artefacts are largely made from amorphous or fine-grained rocks, with an aim towards angular sharp edges (e.g. Figure 4) that may contrast with naturally-deposited rounded or sub-angular stone or coarse sediments. Another attribute that can sometimes be helpful in distinguishing stone artefacts micromorphologically is their minimal weathering compared to other lithic material in the same depositional setting. As stone artefacts are often manufactured from siliceous material, they tend to weather more slowly than other non-siliceous stone. All of these attributes accord with the main micromorphological features of stone artefacts as outlined by Angelucci (2010, 2017; Table 1).

Another potential attribute is the effect of heat treatment, which is a common technique to improve the quality of some flakes and tools (Domanski *et al.* 1994). This involves heating a stone to temperatures of 250–400°C for cryptocrystalline rocks (e.g. chert) and 500°C or above for macrocrystalline rocks (e.g. silcrete, quartzite). Effects of heat treatment include 'crazing' (fine internal cracks), chromatic variation and microstructural changes related to recrystallization of quartz (Angelucci 2017). The latter are best detected by comparing burnt

Table 1
Main micromorphological features of knapped lithic artefacts (from Angelucci 2010, 2017).

Characteristic	Description
Grain size	< 300 μm and often anomalous in respect to grain size of embedding matrix
Alteration	Absent or minimal
Shape and roundness	Tabular or platy, and angular to very angular
Surface roughness	Regular, smooth
Boundary	Sharp, straight to regularly curved

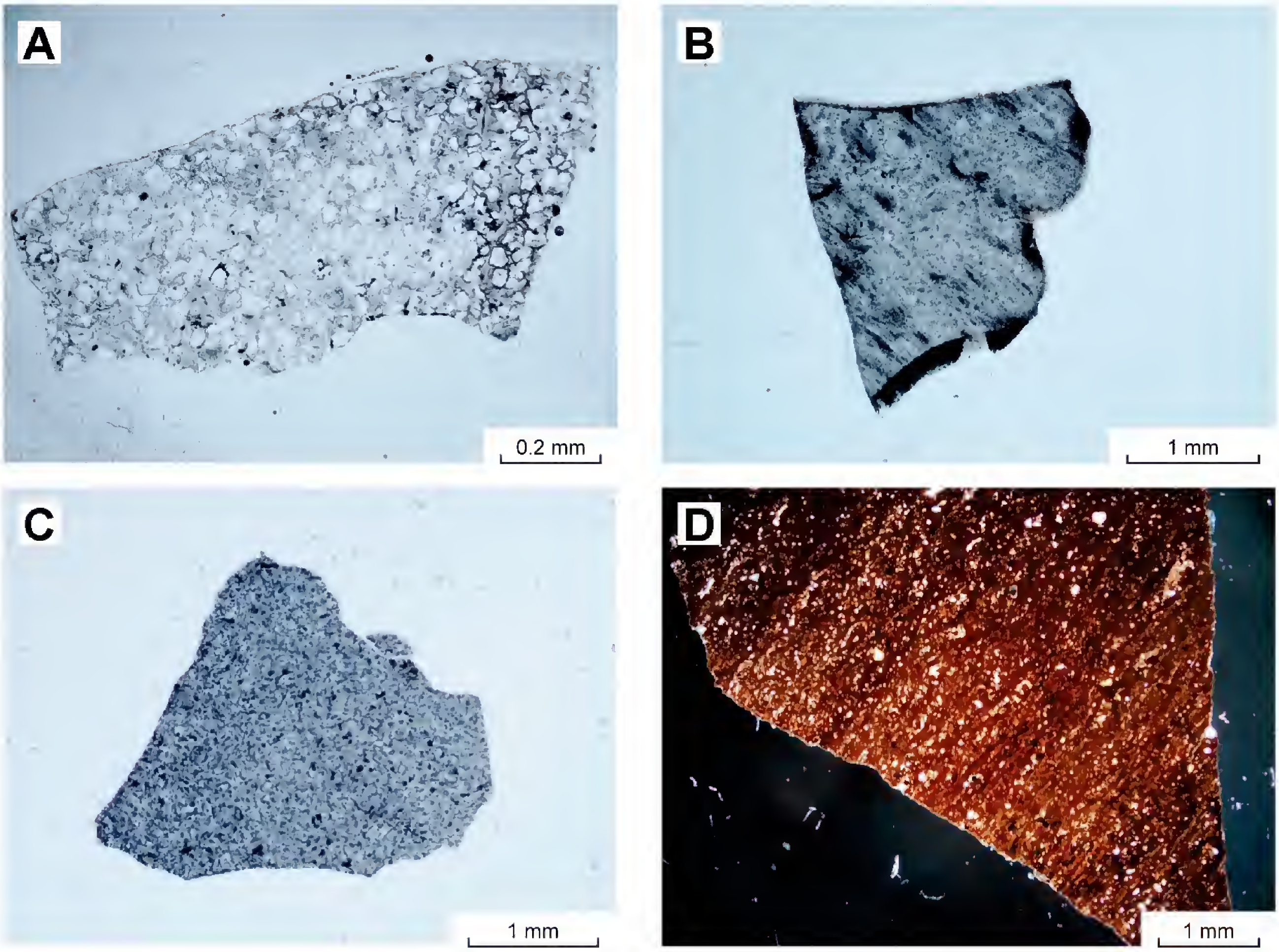

Figure 4. Examples of sharp edges lithic artefacts from Boodie Cave, Barrow Island, Pilbara, including: A, siltstone; B, mudstone; C, basic volcanic; D, ferruginised limestone or 'calcrete'. All images except are PPL except D, which is XPL.

and unburnt artefacts from the same material. Whilst there are no heat-treated artefacts in the current reference collection, this does not mean heat treatment was not used.

Whilst a classification scheme that incorporates both macroscopic and microscopic data would be useful, Martin (1982) emphasized the greater contribution of microscopic characteristics to the identification of artefactual rock types. Figure 4 presents some thin section images of artefacts from Boodie Cave as a guide to their identification in micromorphological sections and, more generally, from basic petrological analyses. Examples include coarser limestone, sandstone and siltstone (Figure 4A) through to the finer grained volcanics (Figure 4C) and mudstones (Figure 4B). A comprehensive guide to the range of stone artefact petrology for Barrow Island can be found in Ditchfield (2016), with results from this work forming part of a larger stone artefact database that is being developed at UWA.

SPALLED ROCK FRAGMENTS (ROCK ART PRODUCTION)

An unusual example of lithogenic material are spalled fragments of painted wall within the sedimentary deposits of Mount Behn rockshelter (Figure 5). These provide a unique insight into early art production techniques and weathering processes at the shelter, with the advantage of not damaging any of the wall paintings. The multilayered fragment reveals pigments of yellow to dark red ochrous minerals, black charcoal and white ash (Finch *et al.* 2013; Vannieuwenhuyse 2016). The identification and geochemical fingerprinting of these mineral pigments can be useful to determine the source of ochres using in rock art (e.g. Ward *et al.* 2001; Huntley *et al.* 2015; Wallis *et al.* 2016).

The micromorphological analysis of spalled rock fragments and surface crusts from rockshelter walls and ceilings can also provide proxy environmental information of changing microclimate and aid dating of underlying paintings and engravings (Watchman *et al.*

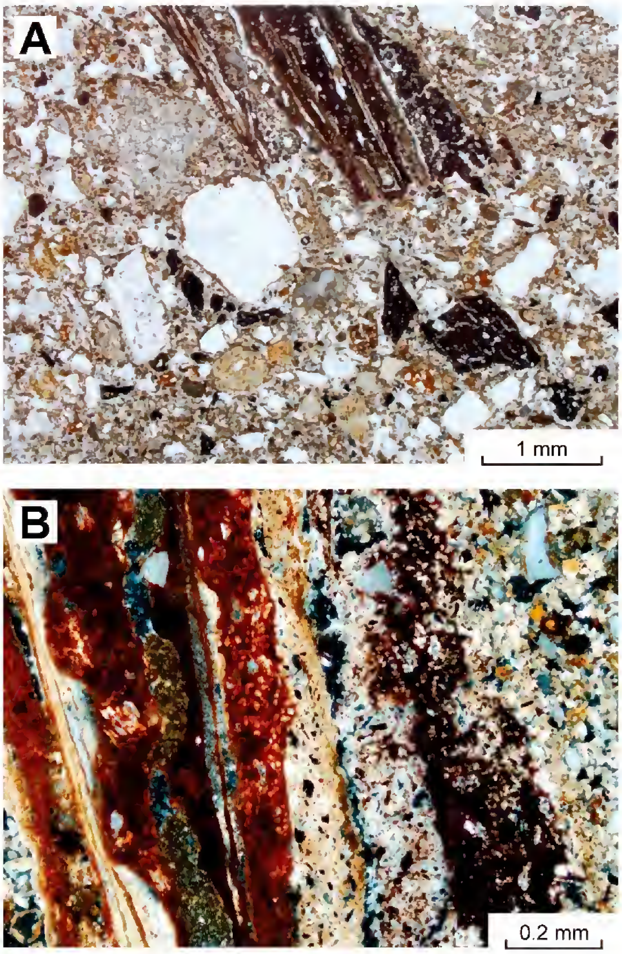

Figure 5. Example of painted wall spall from the Mount Behn sequence, Kimberley (sourced from Vannieuwenhuyse 2016): A, thin-section scan (PPL); B, microphotograph showing the multilayered composition of the fragment (XPL).

2001). Indeed, dedicated research on mineral coatings on the surfaces of sandstone rock shelters in Western Australia's Kimberley is currently underway to find datable materials to bracket ages of rock art motifs with which they are often spatially associated (Green *et al.* 2017).

Biogenic fraction

MOLLUSC SHELL

Molluscan microstructures are highly ordered aggregates of either calcite or aragonite crystals with varied morphologies and three-dimensional arrangements, which may be physically and/or biological determined (Brom & Szopa 2016; Checa 2018). In general bivalve and gastropod shells consist of a non-mineralized layer (the periostracum), with a homogeneous layer embedded between an outer and inner prismatic layer (composed of polymorphs of calcium carbonate) and the iridescent nacreous or porcelaneous layer (composed of tabular aragonite; Canti 2017b). The pigmented organic periostracum is rarely found on archaeological specimens and is not present in any of the reference material (which derive from excavated material). The nacreous shell layer is generally not a reliable discriminating feature (Debryne 2014), hence shell taxa are mainly identified at order or family level from their internal shell composition and arrangement of crystal layers – namely crossed-lamellar, foliate, prismatic and their sub-types (for further detail refer Kobayashi 1969; Claassen 1998; Allen 2017). The different fracture properties of prismatic and nacreous layers of shells are also relevant to the success of different shell-working techniques (Szabo 2008), such as in the ground-edge knives manufactured from baler shell (Akerman 1975), and presumably also to the differential preservation of these layers.

The baler shell (genus *Melo*) is an extremely hard shell (~5 on the Mohs scale) comprised of both sheets of foliated calcite and aragonite (Figure 6A). Indeed Akerman (1975, p. 19) suggested that the absence of ground-edge pearl shell tools on northwest Australian archaeological sites may be explained by the tendency of pearl shells to disintegrate rapidly compared to the much harder baler shell. The pearl shell (*Pinctata* sp.) also has a thin outer calcitic prismatic layer but the middle and inner layers consist of nacreous aragonite (Figure 6B; Taylor et al. 1969). In contrast, *Dentalia* (tusk shell) is entirely composed of aragonite, with a thick middle layer (crossed-lamellar ultrastructure) and two thin surface layers (homogeneous or finely prismatic; Smith & Spencer 2016). The latter were used for making personal ornaments and intentionally fractured segments have been found in archaeological deposits dated as early as 30 000 years ago (Balme & Morse 2006) as far inland as Riwi and Mount Behn (Balme 2000; Balme & O'Connor 2017; Maloney *et al.* 2017).

Crossed-lamellar aragonite also forms the shell for landsnails (Figure 6C), gastropods of genera *Haliotis*, *Nerita* (Figure 6D) and *Anadara* (Figure 6E), whilst layers of calcite and aragonite alternate in *Patella* limpets (Figure 6F; Claassen 1998). *Terebralia* (Potamididae) is similarly composed of both aragonite and calcite (Figure 6G). In oysters (Ostreadidea) the shell is almost entirely of foliated calcite, with a thin outer prismatic layer (Figure 6H). Mussels (Mytilacea) may be wholly aragonitic with nacreous and complex-lamellar structures, or may contain finely prismatic calcitic layers. For example, *Mytilus edulis* has crossed-lamellar (platy) layer over a layer of elongated crystals of calcite, with shells showing up as pink in thin section (see also Villagran *et al.* 2011). This genus is recorded more often in archaeological sites on the east coast and inland of Australia (e.g. Sullivan 1987; Wallis & Collins 2013) than in the west, although the freshwater river mussel (*Lortiella* sp.) has been recorded at Carpenters Gap 3 (O'Connor *et al.* 2014) and mud mussel (*Polymesoda coaxans*) is still collected in the Kimberley (Dilkes-Hall, pers. comm. 2018). More common in coastal archaeological sites are the turreted mangrove whelk *Terebralia palustris* and rocky shore cockle shell *Anadara granosa* (Figure 8F), with the latter stratigraphically overlying the former in several midden sites in northwest Australia (Bradshaw 1995; Clune & Harrison 2009). Whilst understanding past depositional settings may aid identification of economic (edible) shell species, many specimens may still be unidentifiable even with available reference material.

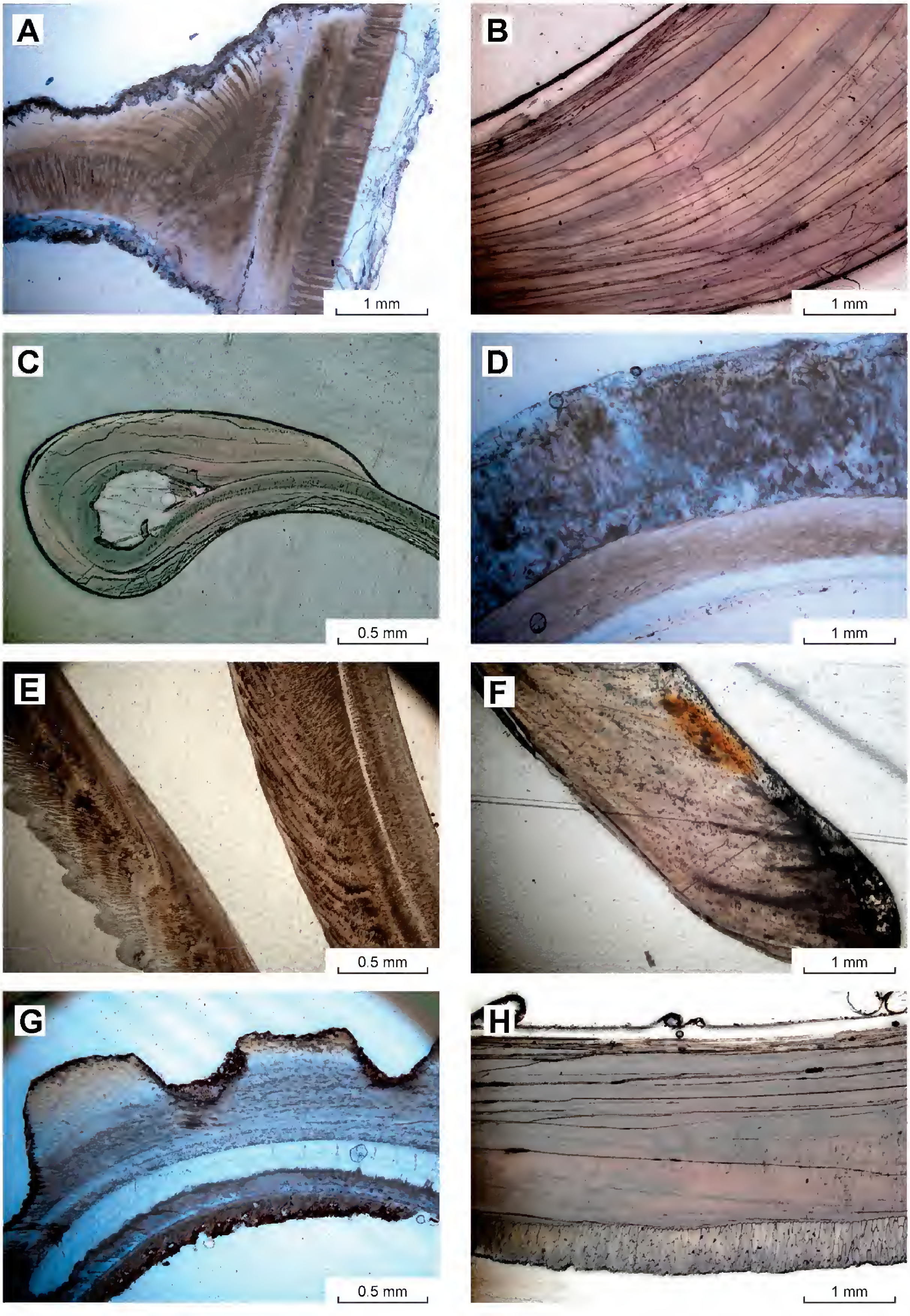

Figure 6. Thin section PPL images of various shells: A, baler shell, *Melo* sp.; B, pearl shell, *Pinctada* sp.; C, landsnail, *Rhagada ballarensis*; D, *Nerita lineata*; E, cockle, *Anadara* sp.; F, limpet, *Patelloida*; G. mangrove whelk, *Terebralia palustris*; H, oyster, Ostredidea.

AVIAN AND REPTILIAN SHELL

Other shell types found in archaeological sites in northwest Australia include avian and reptilian eggshell (Figure 7). As in mollusc shells, eggshell structures are distinguished by the general arrangement of calcite crystals (or aragonite in turtle eggs) ranging from testudoid in Chelonioidea (turtles; Figure 7A), chrocodiloid in Chrocodylia (crocodile) to an ornithoid-ratite morphotype in Struthionidae (emu; Mikhailov *et al*. 1996). Whereas crocodilians and some turtles lay eggs with tough shells the soft, leathery nature of most reptilian eggs mean that do not preserve well in most archaeological sites. The presence of turtle bone in midden deposits, such as Boodie Cave (Veth *et al*. 2017), are evidence that they constituted part of the dietary assemblage of this region.

Under the microscope, avian eggshells (Figure 7B) typically reveal edge columnar crystals (the palisade/ mammillary layer) whereas mollusc shells display interwoven fibrous crystals (Durand *et al*. 2018). When the thin section is viewed obliquely against a dark background, avian eggshell will also stand out as a white line in contrast to mollusc shell, which is more transparent (Canti 2017a). Avian eggshells, some of which is possibly burnt (Figure 8A, B), have been recovered from excavations in many sites in both the Pilbara (Ward *et al*. 2017) and Kimberley (Vannieuwenhuyse 2016; Vannieuwenhuyse *et al*. 2017).

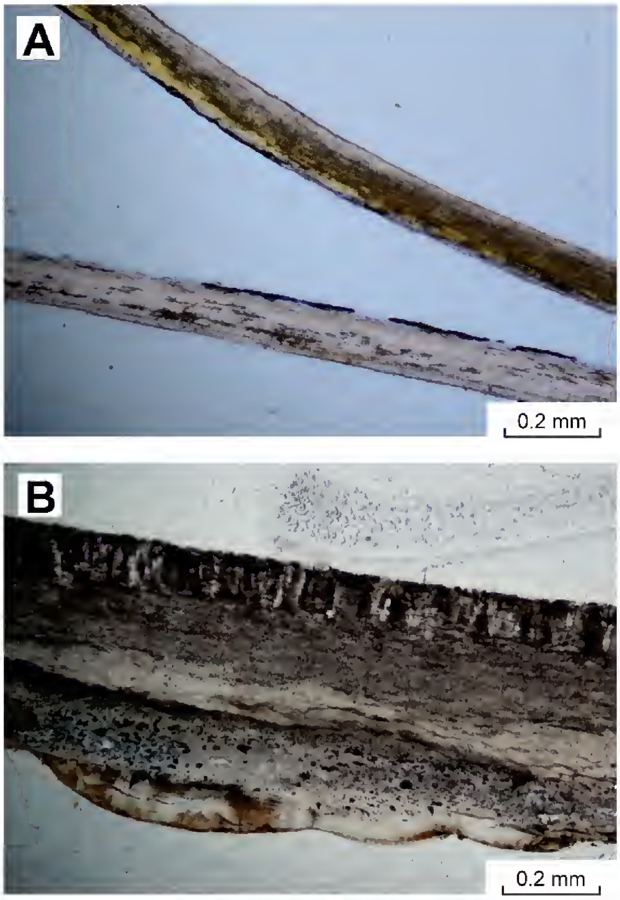

Figure 7. Thin section PPL views of: A, marine turtle, Barrow Island, Pilbara; B, modern emu eggshell.

In larger emu eggs, the mammillary layer can be up to one-third of the shell thickness with a radial, wedge-like arrangement of the columnar crystals, whilst the continuous inner layer has pronounced, horizontal growth lines (Long *et al*. 1998). In addition, the palisade layer tends to be less porous than for other avian species. Although not observed in Boodie Cave, emu eggshell was recorded at Cape Range, southwest of Barrow Island, alongside crab, sea urchin, fish and ochre in deposits dated before ~ 26 ky BP (Morse 1993a, 1993b).

Contextual examples

Heated or burnt marine or other shell is not explicitly included in the shell reference material except within the context slides (see below). The two main types of alteration in burnt carbonates are scorching between 300–700°C and calcining at temperatures above ca. 800°C (Canti 2017c). The former produces progressive darkening (Figure 8B) whilst the latter produces isotropic calcium oxide that may reform to (cryptocrystalline) calcium carbonate under moist conditions. Darkened shell is more common in midden deposits of northwest Australia (Ward *et al*. 2017) and may indicate low temperature heating of shells in order to open rather than cook them.

It should be noted, however, that discolouration of mollusc, crustacean and echinoderm shell can also relate to residence time in the intertidal zone and/or sedimentary context (Kolbe *et al*. 2011; Powell *et al*., 2011). In the case of the larger foraminifera *Alveolinella quoyi* (Figure 7C) the dark brown colour in thin section is typical of exceptionally well-preserved tests, which are white in reflected light. The test wall is composed of high-Mg calcite (very susceptible to corrosion) and is made of minute randomly oriented rod-like crystallites, which inhibit the passing of transmitted light.

The pigmented organic periostracum of molluscs can also be destroyed by heating above 300°C and/or from degradation from organic acid in the soil (Villagran *et al*. 2011; Villagran & Poch 2014), hence is unlikely to be encountered in most northwest Australian contexts, and was not observed in any of the archival material. Of the inorganic component, calcitic shell is generally harder, denser and less soluble than aragonitic shell, and thus more likely to survive (Claassen 1998). However, in Boodie Cave (Veth *et al*. 2017) shell remains of *Nerita* sp. can preserve relatively well for long periods (here dated to 40.3 – 42.5 ky BP, WK-42542) because they have a calcitic outer prismatic layer, which is less stable than aragonite found in the outer and inner layers of almost all other gastropod groups (Cox 1969). However, it is important to check recrystallization at the nanoscale to avoid any biased isotopic signatures (Weiner 2010). Also, well preserved in Boodie Cave are baler shell fragments (Figure 8D) and also intact serrated baler spoons or 'sporks' (Veth *et al*. 2017). In many coastal midden sites of northwest Australia, more deeply buried shell tends to be 'sacrificed' or degraded relative to the uppermost shell layers, despite the alkaline conditions provided by the carbonate (Clune 2002). This reflects a general decalcification of shell under more acidic conditions and hence is more apparent where middens have accumulated away from the immediate

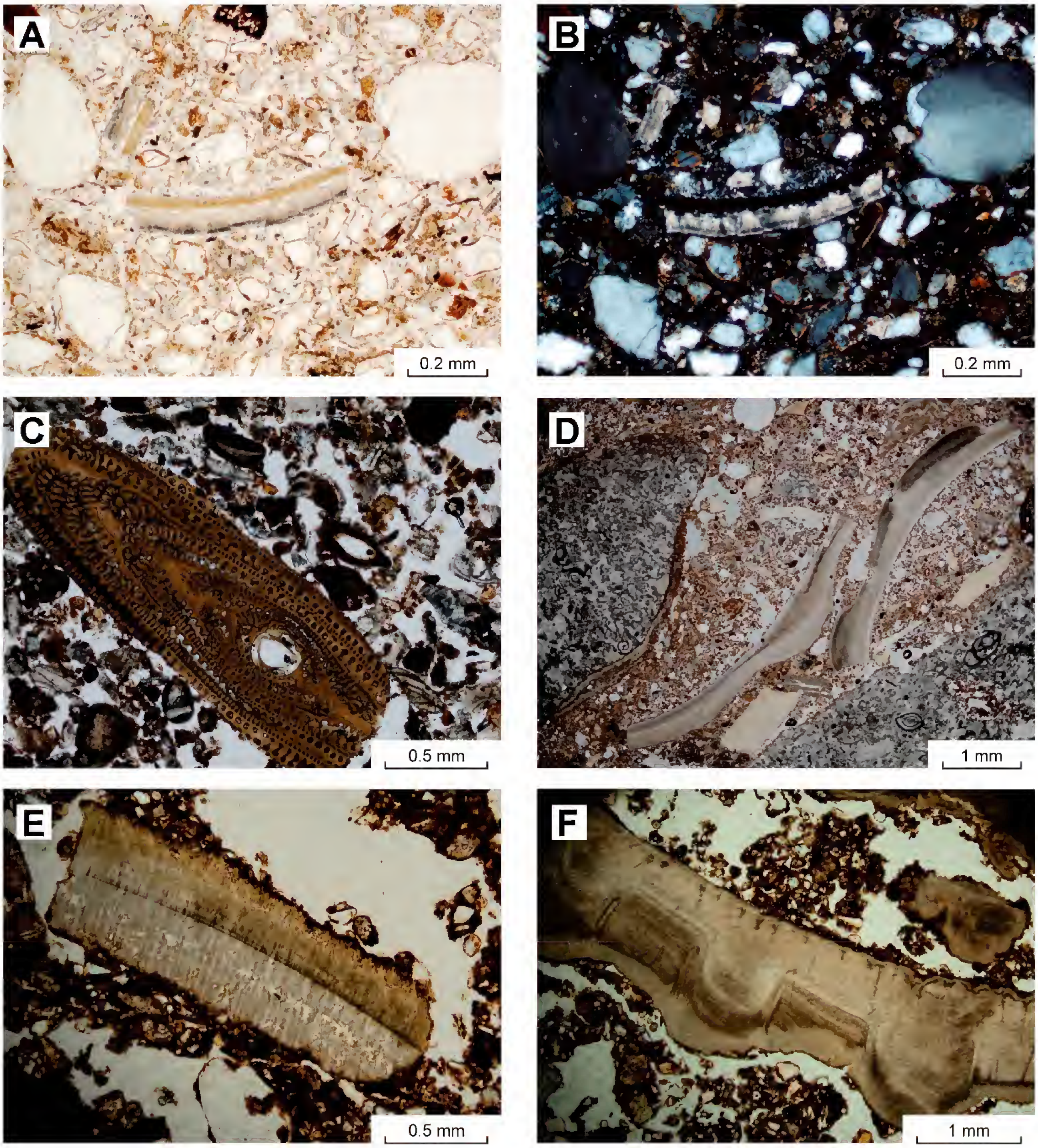

Figure 8. Examples of shells found in Kimberley and Pilbara archaeological sites: A & B, avian eggshell, possibly burnt (PPL & XPL, Riwi, sourced from Vannieuwenhuyse 2016); C, centred axial section of the foraminifera *Alveolinella quoyi* (not discoloured; Boodie Cave); D, baler shell fragments (Boodie Cave); E, decalcified cockle shell in a midden deposit (Dampier Archipelago); F, cockle (*Anadara* sp.) in ferruginous siliciclastic matrix (Dampier Archipelago). All images are PPL unless otherwise specified.

coast and over sediment derived from volcanic rock such as on the Burrup Peninsula (Figure 8E). Shell may also show increasing fragmentation due to reworking by cyclone or storm events in middens nearest the contemporary coast (Clune 2002). In this regard and more generally, micromorphological analysis of shell should be considered as an aid to macromorphological studies to provide some relationship with the deposits in which they occur and gain a more holistic view of site formation (Canti 2017b, p. 46).

EXCREMENTS

Dung is more common in archaeological sites than is perhaps realized, and in some cases may be the only evidence for the presence of species not represented among the bone remains (Linseele *et al.* 2013). Criteria for micromorphological identification are best achieved through a combination of morphometric features, associated content (e.g. plant remains, bone fragments) and again aided by reference collections (*ibid*). Fresh herbivore excrements are usually porous, loosely packed and consist mainly of poorly digested to undigested plant fragments, sometimes embedded in a brown to dark brown amorphous organic groundmass that becomes darker and/or redder with weathering due to humification or oxidation (Brönnimann *et al.* 2017a). Whilst carnivore coprolites typically contain bone fragments and optically isotopic matrix, their diet and feeding habits make them much more diverse (Brönnimann *et al.* 2017b).

The content of excrements from fauna on Barrow Island, a Class A reserve, are considered to reflect more pristine native environments than on the adjacent developed mainland coast. As in most Australian contexts, the scats of wallabies and kangaroos are small and round with a dry grassy matrix inside (Figure 9A, B). The dense outer rim of these scats mean they are less likely to disintegrate. Along with several other grasses, part of the diet for the euro on Barrow Island is thought to be the developing flower stalks and growth tips of spinifex (*Triodia* sp.), whilst the diet of the wallaby consists of grasses and some fruits, leaves of shrubs, and figs. The northern brushtail possums are omnivorous and nocturnal and hence do most of its foraging for leaves, flowers and fruits during the night but have been seen to feed on insects (Russell *et al.* 1989), as evidenced by the occasional chitin fragment in thin section (Figure 9C). The scats of large possums, such as brushtails (*Trichosurus* sp.) and scaly tails (Wyulda), produce generally dark, cylinder-shaped scats, whereas smaller possums, such as the pygmy (*Burramys* sp. and *Cercartetus* sp.), leave rat-sized pellets.

Bandicoots are omnivorous: their diet includes ants, termites, moths, turtle eggs and hatchlings, small reptiles, roots and tubers (Russell *et al.* 1989 Figure 9D). The nocturnal burrowing boodie is also omnivorous, and feeds on a variety of fruits, seeds, nuts, flowers and termites and hence has more of a vegetal component in its excrements (Figure 9E). Microbats, such as *Vespadelus finlaysoni*, eat a variety of small insects, hence their scats as found in Boodie Cave have a high chitin component (Figure 10D). Parente are carnivorous, consuming invertebrates and occasionally small vertebrates such as geckos and lizards as well as insects. Studies of monitor lizards has shown that individuals will specialise on whatever food items are available in their habitat (Traeholt 1997), including foraging amongst construction camps for small mammals and foraging gulls (Losos & Greene 1988). On Barrow Island, scats of *Varanus giganteus* consisted primarily of sea turtle eggs and hatchlings, and small mammals (Losos & Greene 1988). Figure 9G and H, show one such scat with highly birefringent, well-orientated elongate crystals of turtle egg and probably hair around an isotropic bone.

Contextual examples

Both herbivore and carnivore faeces were identified in the Carpenters Gap 1 and Riwi sequences (Vannieuwenhuyse 2016; Vannieuwenhuyse *et al.* 2017) and also Boodie Cave (Ward *et al.* 2017) suggesting animal occupation of the shelters (Figure 10A–F). The main implication of herbivorous scats (Figures 10A, B) is that partly degraded plant material in sediment profiles of archaeological excavations may not be cultural but rather a by-product of animals, and further indicates (alongside excremental fabrics) probable reworking of sediments. Similarly, bone from economic species, such as euro, hare-wallaby, golden bandicoot, brush-tail possum and even snakes and lizards, may actually represent remains of non-human prey rather than a product of human consumption (Manne & Veth 2015; Veth *et al.* 2017; Figure 9F). In these cases differences in fragmentation determined from whole fragments of micro- and small-bodied fauna may provide better indication of an anthropogenic origin.

Thin sections are more informative of post-depositional modification. Under relatively moist conditions, the decay of organic matter can lead to an enrichment of phosphate and hence to phosphate precipitations in or around the excrements (Canti & Brochier 2017). In Boodie Cave and Riwi, gypsum and/or anhydrite crystals were observed around bone and also phosphatic-rich faeces, such as bird droppings (Figure 10E). In well-drained sediments (neither waterlogged nor desiccated) organic material is usually not preserved and instead microscopic bio-mineral components like silica phytoliths or calcitic crystalline faecal spherulites (5–15 μm, Figure 10B) may be the only indication of presence of organic matter in the past (Canti & Brochier 2017).

However, spherulites are easily dissolved hence generally only survive in alkaline sediments or where water throughflow is minimal, such as limestone caves or rockshelters. Some examples include Boodie Cave (Figure 10C) and also Carpenters Gap 1 (Vannieuwenhuyse *et al.* 2017). They are also found in open areas characterised by rapid burial, aridity or a high pH in the sediments but are destroyed by heating at high temperatures (> 500°C; Canti & Brochier 2017). Whilst bushfire flames easily reach such temperatures, surface soil temperatures are generally buffered below 200°C and decrease with depth (McKenzie *et al.* 2004; Singh *et al.* 1991), hence spherulites should in theory not be affected.

Macro and micro-botanical fraction

As indicated, UWA hosts existing and growing anthracology (wood charcoal) and carpological (seeds and fruits) reference collections from the Pilbara and Kimberley regions (Byrne *et al.* 2013; Dilkes-Hall 2014: Dotte-Sarout *et al.* 2015). These types of remains generally require identification from more than one cross-sectional angle and/or in three-dimensions by specialist archaeologists, and hence are less suited to a thin section reference collection. Microbotanical remains include ash, phytoliths, pollens and spores, starch, diatoms and other microfossils. Identification of these particles in thin sections is described in relevant chapters of Nicosia and Stoops (2017). Northwest Australian regional studies and reference collection are still scarce, especially those related to archaeological contexts (Wallis 2001).

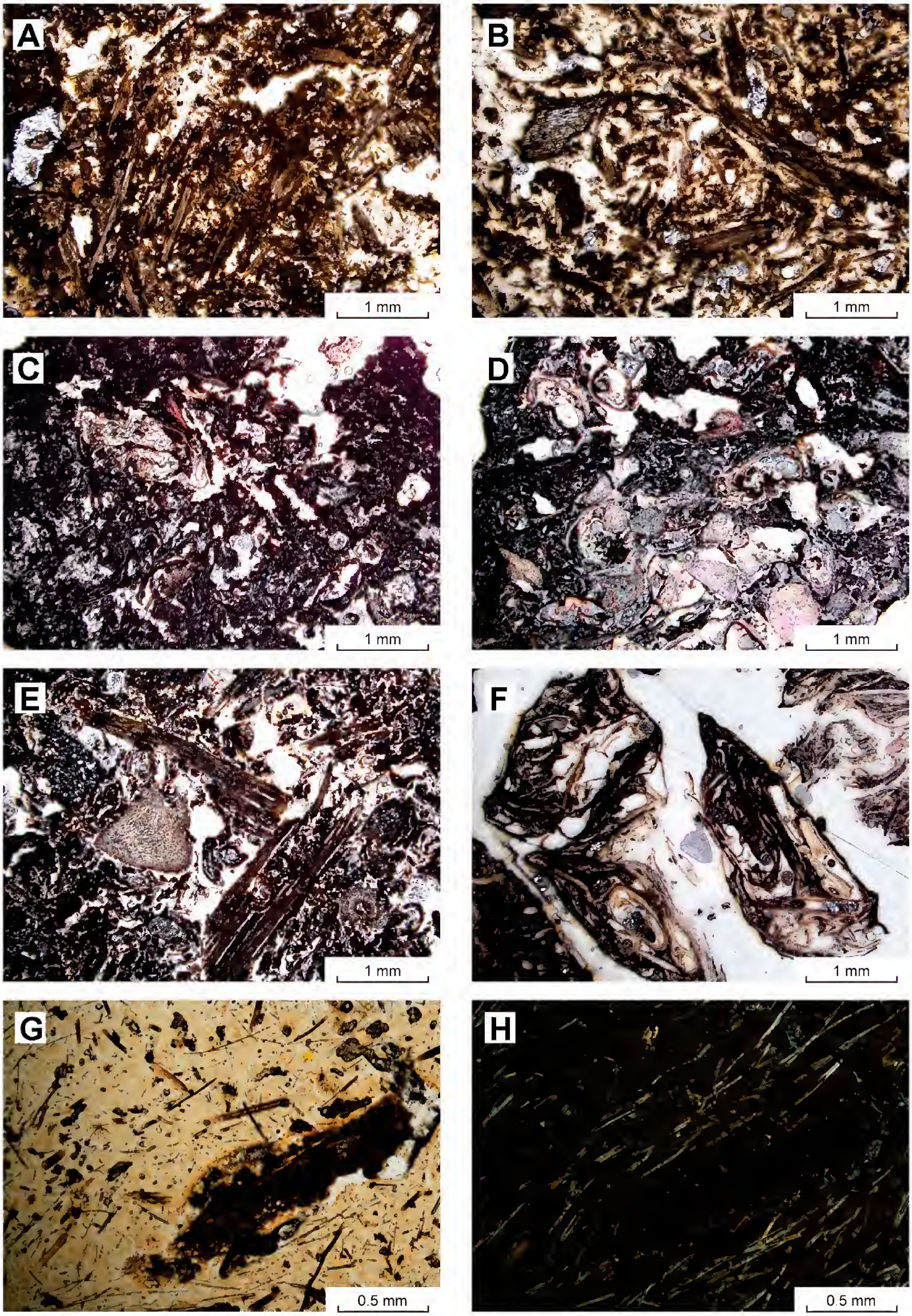

Figure 9. Thin-section microphotographs of native fauna scats from Barrow Island: A, euro, *Macropus* sp.; B, Wallaby, *Petrogale* sp.; C, possum, *Trichosurus* sp.; D, bandicoot, *Isodon* sp.; E, burrowing boodie, *Bettongia* sp.; F, microbat, *Vespadelus* sp.; G, H, parente, *Varanus giganteus*. All images are PPL except H, which is XPL.

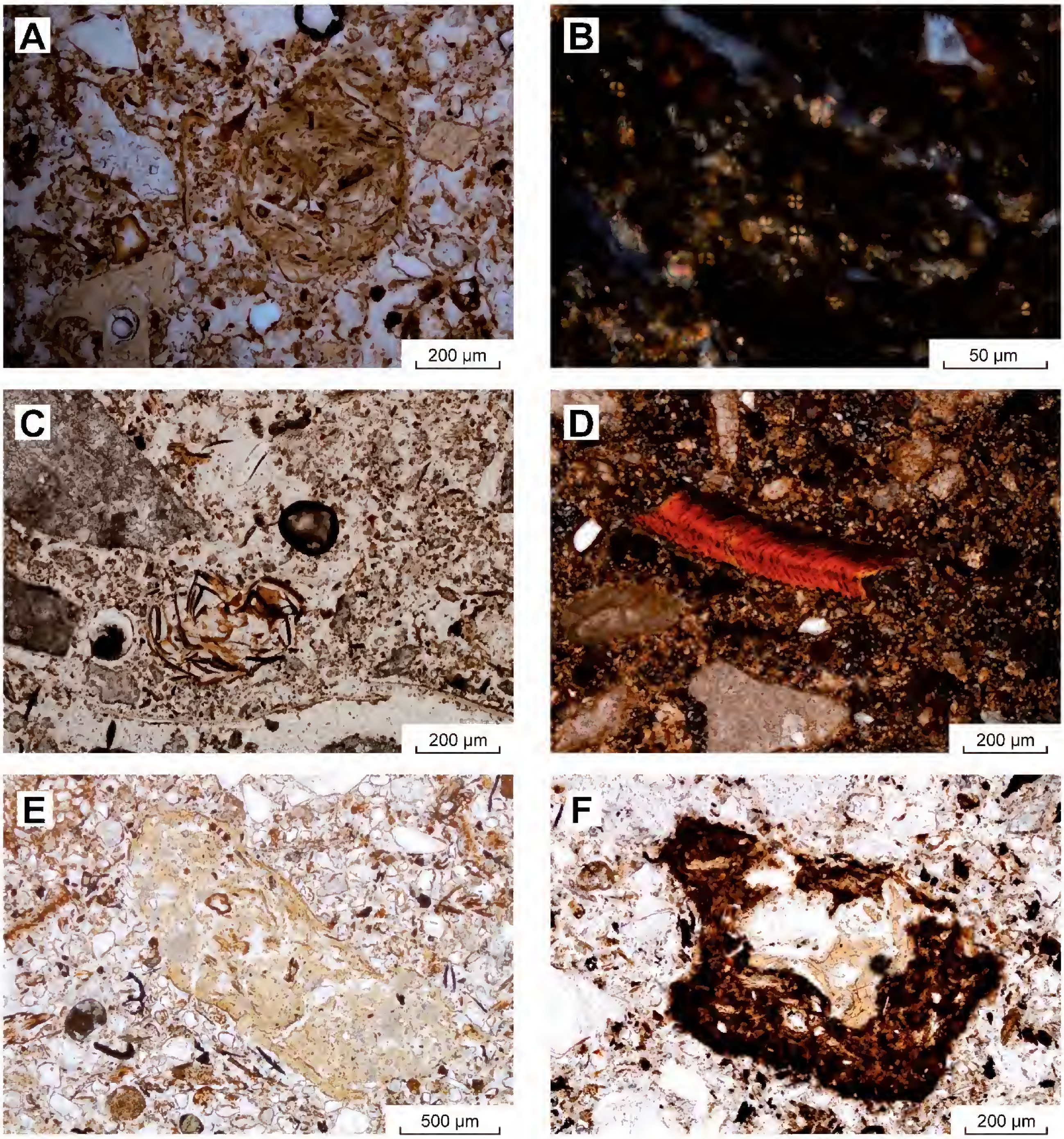

Figure 10. Microphotographs of scats found in Kimberley and Pilbara archaeological sites: A, partially digested plant matter in well preserved macropod coprolite (PPL, Boodie Cave); B, same as A, at high magnification showing spherulites with typical cross-pattern extinction (XPL); C, microbat scat with insect chitin (PPL, Boodie Cave); D, chitin (insect parts, XPL, Boodie Cave; Ward *et al*. 2017); E, apatite-rich bird dropping with vegetal tissue residues and phytolith inclusions (PPL & XPL, Riwi, Vannieuwenhuyse 2016); and F, carnivorous scat with bone fragments (PPL, Carpenters Gap 1, Vannieuwenhuyse *et al*. 2017).

Palaeobotanical analyses extend the focus to human signatures rather than simply palaeoenvironment. A large focus has been given to the micromorphological study of combustion features, documented in many publications (refer Nicosi & Stoops 2017 and references therein). The palaeobotanical and micromorphological analysis of combustion features have proven to be quite informative in terms of human behaviour (plant collection, food production and various use of light and heating properties), as demonstrated by the combined anthracological and micromorphological results from Riwi combustion features (Whitau *et al*. 2017).

Microbotanical particles such as ash and phytoliths have a commonly polymorphic nature, which means that

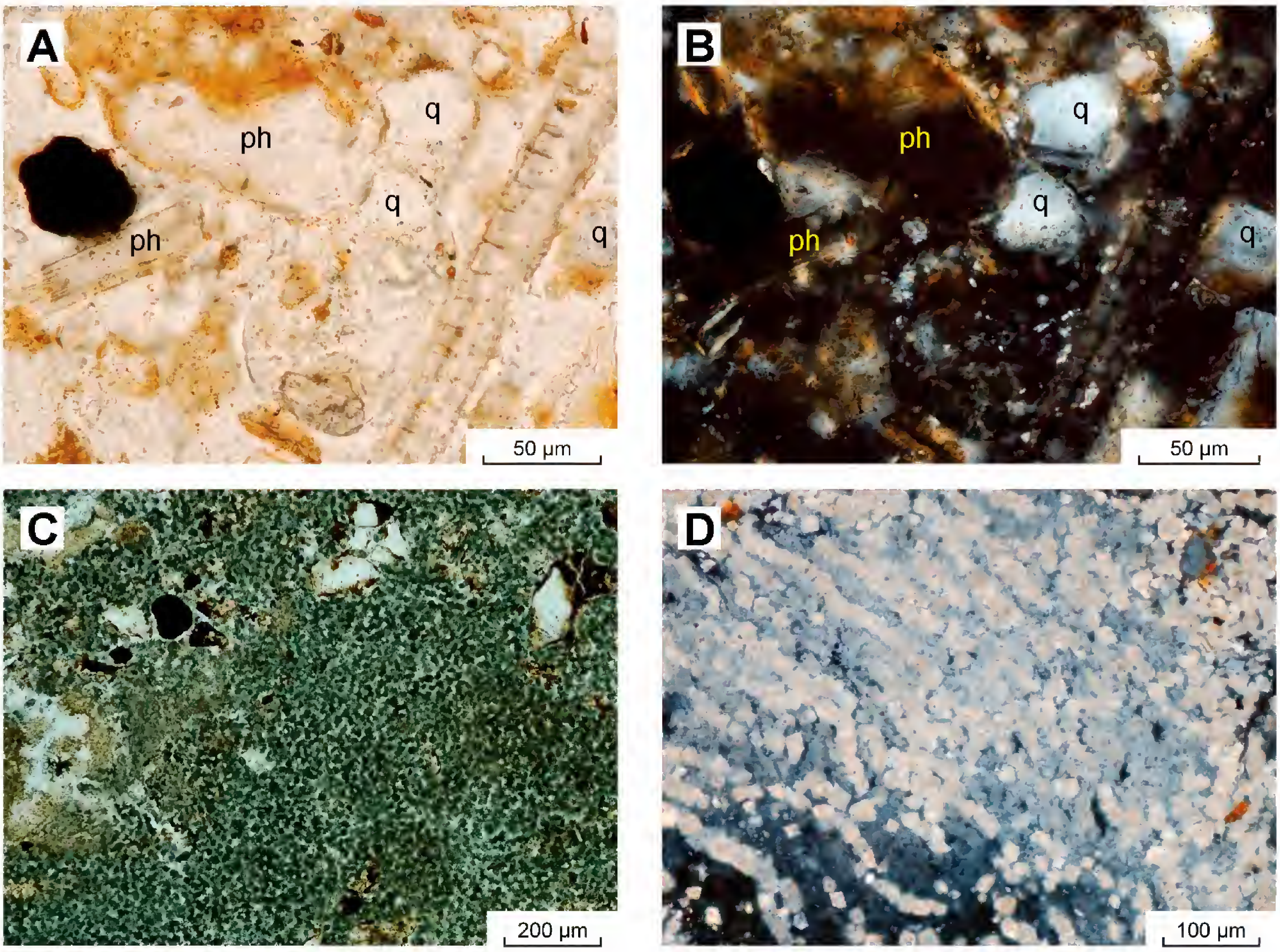

Figure 11. Microphotographs of polymorphic phytoliths in Riwi: A&B (PPL & XPL) are sourced from Vannieuwenhuyse (2016) and Whitau *et al*. (2017); and C&D (PPL & XPL) showing phytoliths that are typically anisotropic in XPL and calcitic rhomboedric ash particles.

similar shapes can be found in different wood species and there may be different shapes in the same wood species (Wattez 1988; Brochier & Thinon 2003). While studies in the Kimberley have demonstrated that phytoliths have a high range of polymorphism (e.g. Wallis 2001, Figure 11A and B), calcitic ash particles observed in archaeological sequences all have a similar rhomboidal shape (Figure 11C and D). This is probably best explained by the similarity in woody anatomical structure among Australian Eucalypt and Acacia species (observations based on anthracological study, Whitau & Dotte-Sarout, pers. comm. 2015).

Preservation of plant and charcoal are best explored by identifying the effects of post-depositional processes using micromorphology. For example, the mineralisation of wood charcoal in Boodie Cave was presumably produced by precipitation of minerals from water dripping through the cave ceiling (Ward *et al*. 2017). Similar examples of secondary carbonates or gypsum growing in charcoal voids have been observed in karstic contexts in Australia and France (DV personal observation) so may be a common phenomenon of limestone caves in arid zones.

DISCUSSION

Creating and sharing reference collections

The extreme weathering conditions of northern Australia exacerbate the poor preservation of largely temporally and spatially discontinuous archaeological and environmental evidence left by mobile Aboriginal occupation. Micromorphology thus allows for a forensic style characterisation and analysis to aid any or macro-scale study of archaeological sites; and, perhaps more critically, providing information about the formation history and integrity of cultural material and their microstratigraphic context.

According to Hughes (1983, p. 114):

> *A wealth of information can be gained from the analysis of thin sections of samples of impregnated deposit (...). However, (...) the preparation of the samples and their subsequent analysis is a specialised, expensive and time-consuming process that only a few institutions in Australia are capable of undertaking. For these reasons thin section analysis should only be considered for long-term archaeological projects of an interdisciplinary nature.*

Although time-consuming, most institutions have a geological facility capable of preparing inexpensive thin sections. Unfortunately the large micromorphological thin sections, typically 5 x 7 cm or more, needed to better understand depositional and post-depositional features (Courty *et al.* 1989) are more expensive to produce. Nevertheless, it must also be taken into consideration that large thin sections can supplement and/or replace mineral identification (e.g. X-ray diffraction) and grain-size analysis (especially identifying grain size of different minerals), or can be used for complementary analyses such as scanning electron microscopy and quantitative mineral mapping (e.g. Ward *et al.* 2018). Thin sections are particularly useful in detecting diagnostic remains or features that would otherwise be overlooked in any macro-scale analysis, such as the painted wall fragments from Mount Behn rockshelter or microcharcoal fragments in cultural units where macroscopic evidence of charcoal or burning is entirely absent (Lowe *et al.* 2018). Regardless of any sophisticated techniques, as Courty (1991) reminded us, the primary goal of micromorphology is understanding sedimentary context.

Another consideration is the destructive aspect of thin section analysis, particularly for stone artefacts. Nevertheless, numerous examples demonstrate the value of stone artefact petrology to determine the provenance of such items (e.g. Binns & McBryde 1972; Glover *et al.* 1975; McBryde & Watchman 1976; Martin 1982; Benbow & Nicholson 1992; Webb *et al.* 2013; O'Leary *et al.* 2017). From a broader micromorphological perspective it is not just the potential source of stone artefacts that is of interest but also what they might indicate about depositional and post-depositional history. For example, different patterns of heat fracturing (both cracking and shattering) may be important in identifying deliberate heat treatment as opposed to natural transformation through fire (Mercieca 2000). Similarly, orientation might provide clues to directional water movement, sloped deposits or even faunal activity (Vannieuwenhuyse 2016), whilst petrons or other forms of size sorting may be indicative of a lag deposit or development of stone lines through bioturbation (Fitzpatrick 2012), all of which may be important in distinguishing natural from cultural deposits and/or their stratigraphic integrity (Hiscock 1985).

There can be great value in undertaking micromorphological analyses for short-term and single site studies, for example, to aid facies characterisation and integrity of any radiometric dating (e.g. Janowski *et al.* 2015; Green *et al.* 2017; Vannieuwenhuyse *et al.* 2017; Ward *et al.* 2017). It is encouraging to see micromorphology techniques increasingly being integrated with standard sedimentological (including geochemical), geochronological and magnetic susceptibility analyses to better understand the record of human impact and site formation processes and site integrity (Clarkson *et al.* 2017; Lowe *et al.* 2018). It has also been applied successfully to understand site formation of abandoned mud brick structures in arid environments in the near East (Friesem *et al.* 2011), which may find analogy in the historic wattle-and-daub structures in Australia and elsewhere (Kruger 2015).

In isolation the small-scale data offered by micromorphology is generally insufficient to reach meaningful interpretations of archaeological site formation. Rather it works best in conjunction with other microscale (e.g. mineralogy, palynology, phytolith and isotopic analyses) and macro-scale evidence (e.g. lithic analysis, zooarchaeology, anthrocology, archaeomalacology) as a guide to intra-deposit relationships and to gain a more holistic view of site formation (e.g. Villagran *et al.* 2011; Vannieuwenhuyse *et al.* 2017; Ward *et al.* 2017; Whitau *et al.* 2018a, 2018b). As Courty (1991) explained, micromorphology is best utilised when combined with other methods to answer specific questions.

The time-consuming aspect of micromorphological analysis is perhaps unavoidable but objective comparison of sediments and component features can be significantly aided by development of reference databases and contextual (large thin section) studies. The UWA archaeological micromorphological reference collection is themed around material from northwest Australia and will hopefully be expanded in future years. This is important as the present reference collection is unlikely to be representative of the wide range of archaeological contexts of this region. Even this preliminary micromorphological reference collection demonstrates how different the types of remains, contexts and site formation processes can be in northwest Australia compared to more temperate regions.

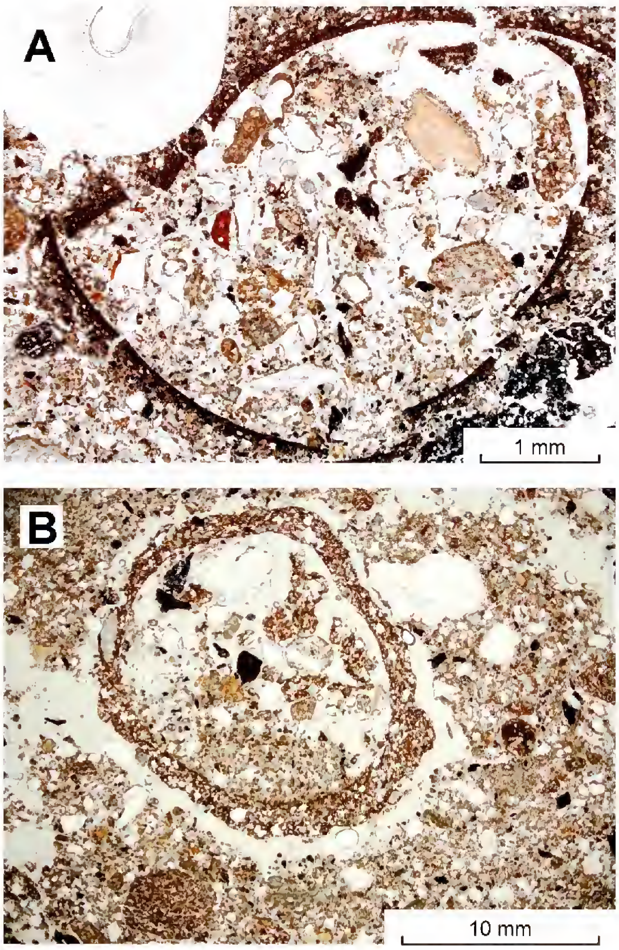

Figure 12. Insect galleries from Mount Behn (both PPL, sourced from Vannieuwenhuyse 2016).

As noted by van der Meer & Menzies (2011, p. 228), for the plethora of individual microstructures within sediments, it is the overall assemblage that is more indicative of a particular sedimentary environment than any single microstructure type. More typical of arid and semi-arid contexts, for example, are dissolution features (especially of carbonates and phosphates including bone, ash and guano); calcification (cave breccia, secondary carbonates) and argillic, calcic, and gypsic features. Examples of many of these are present in the caves, rockshelters and open sites of northwest Australia (Vannieuwenhuyse 2016; Ward *et al.* 2017) and other sites in arid and semi-arid zones (e.g. Amit & Yaalon 1996; Khademia & Mermut 2003). Biological activity can also offset or obscure effects of other processes (Courty & Fédoroff 1985). For example in arid and semi-arid zones termites and other burrowing arthropods (e.g. mudwasps, antlions, burrowing bees) essentially fill the role of earthworms in more temperate climates (McBeaty 1990; Williams 1978; Figure 12) and probably play a greater role in post-depositional disturbance than larger fauna (Venn 2008; Kourampas *et al.* 2009; Vannieuwenhuyse *et al.* 2017).

The reference collection provides a preliminary valuable regional reference against which to help identify archaeological and non-archaeological (including post-depositional) remains and features in thin sections obtained from other sites in northwest Australia and in other arid-zone areas. Just as with the anthracology reference collection (Dotte-Sarout *et al.* 2015), the micromorphology reference collection ultimately needs to be transformed into an atlas or database that is readily available to help with the development of the discipline in this and other arid and semi-arid zone regions. To this end, the reference collection supplements the comprehensive micromorphological and encyclopaedic references of Stoops *et al.* (2010) and Nicosia & Stoops (2017). We will continue to build on our arid zone database as comparative experimental studies and reference collections for cooler climates (e.g. Villagran *et al.* 2011; Banerjea *et al.* 2015) show that such databases are invaluable aids for the identification of anthropogenic sctivity.

CONCLUSION

Although archaeological micromorphology is still a developing field in Australia, new projects focused on prehistoric sites are starting to reverse this trend (and may eventually extend to historical and marine contexts). The examples presented for northwestern Australia indicate that there is great advantage in developing local frameworks and resources for micromorphological and related work. Whilst acknowledging the conceptual capacities to process micromorphological data already collected and continually increasing, the development of archaeological micromorphology, as Courty (1991) explains, requires a close collaboration with archaeologists, using relatable terminology and an understanding of common objective towards understanding past human activities and the associated environmental context (see also Goldberg & Aldeias 2016). The best way to achieve this is through collaborative projects associating archaeologists, geoarchaeologists and other specialist scientists, so that adequate samples can be obtained from excavations. Such datasets are useful in teaching and training but ultimately are aimed at strengthening, or transforming, interpretation of archaeological sites in these Australian dryland contexts.

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